**US Army Corps
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Waterways Experiment
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Wave Information Studies of U.S. Coastlines

Hindcasting Swell from the Southern Ocean Along the U.S. Pacific Coast

*by   J. M. Hubertz, J. B. Payne, WES
      P. D. Farrar, Stennis Space Center*

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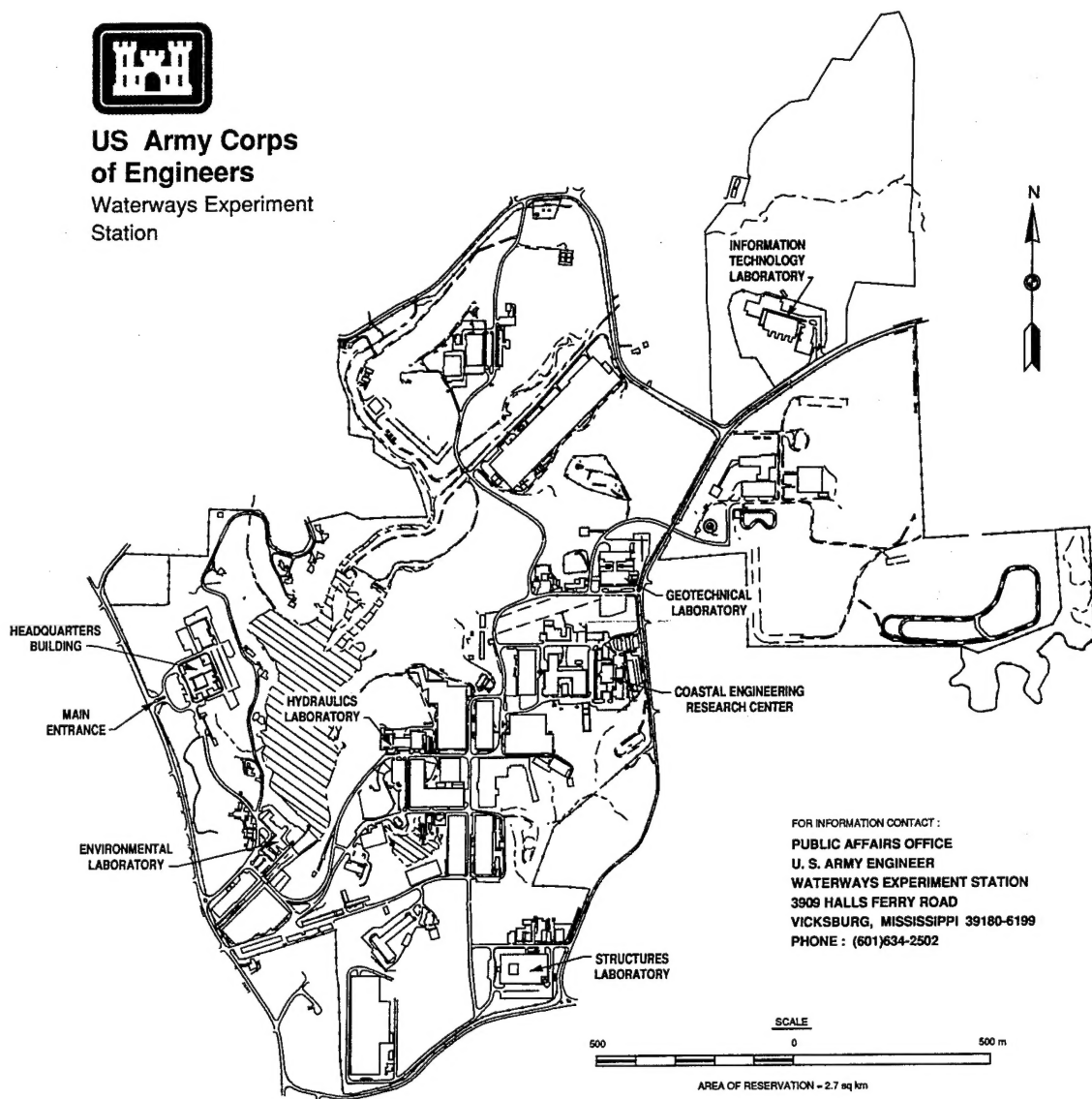Stennis Space Center
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Final report

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LABORATORY

SCALE

500   0   500 m

AREA OF RESERVATION = 2.7 sq km

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Preface

This report describes the approach used to hindcast swell, which originates from storms in the Southern Ocean, and subsequently arrives along the U.S. Pacific coast. This study was performed by the U.S. Army Engineer Waterways Experiment Station (WES) Coastal Engineering Research Center (CERC) under the Wave Information Study (WIS) Work Unit 12114, Field Data Collection Program, authorized by Headquarters, U.S. Army Corps of Engineers (HQUSACE). Messrs. John H. Lockhart, Jr., and John G. Housley were the HQUSACE Technical Monitors. Ms. Carolyn M. Holmes was CERC Program Manager. Dr. Jon M. Hubertz was WIS Project Leader.

This report was prepared by Dr. Jon M. Hubertz and Ms. Jane B. Payne, both with the WIS Group at CERC, and Mr. Paul D. Farrar, formerly of the WIS Group at CERC, and presently at the Naval Oceanographic Office. The WIS Group is part of the Coastal Oceanography Branch (COB), CERC, WES, and this report was written under the direct supervision of Dr. Martin Miller, Chief, COB. General supervision was provided by Mr. Lee Butler, Chief, Research Division, CERC. Dr. James R. Houston was Director of CERC, and Mr. Charles C. Calhoun, Jr., was Assistant Director.

During publication of this report, Dr. Robert W. Whalin was Director of WES, and COL Bruce K. Howard, EN, was Commander.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
knots (international)	1.8532	kilometers per hour
miles (U.S. nautical)	1.852	kilometers

1 Introduction

Objective and Scope

This report documents the approach used to hindcast swell originating in the Southern Ocean and arriving along the U.S. Pacific coast. Hindcast information is compared with directional wave measurements in deep water away from the influences of islands and shoals along the coast, as an example of the agreement achieved. The scope of this study is confined to the accurate generation of swell in the Southern Ocean from available wind information and propagation to the U.S. west coast in deepwater regions outside the islands and shoals along the coast.

Hindcast wave information along the Pacific coast is available from a number of sources, one of which is the Wave Information Studies (WIS) conducted by the U.S. Army Engineer Waterways Experiment Station (WES), Coastal Engineering Research Center (CERC). This study has produced five reports summarizing climatic wave conditions for the Pacific coast (Corson et al. 1986; Corson et al. 1987; Jensen, Hubertz, and Payne 1989, Tracy and Hubertz 1990; Jensen et al. 1992). Each of these reports covers the time period 1956-1975. During that time period, little wind information was available over the Southern Ocean region. Thus, reliable hindcasts of swell arriving from this location were not possible.

This southerly swell component of the wave climate is important to coastal processes. Although relatively low in height, typically 0.5 to 1.5 m in deep water, these waves have long periods (13 to 20 s) and will shoal and be a major force in the breaker zone. This swell is most frequent in the Northern Hemisphere summer when other sources of swell from the North Pacific are usually absent. Thus, southern swell may be the dominant force producing longshore currents. Extreme swell heights may also occur, resulting in breaking wave heights of 3 m or more.

This study applies the production version of the WIS wave model WISWAVE 2.0 to hindcast southern swell and verifies the hindcast results by comparison with measured directional data.

Background

Waves striking the coast can be the products of a local wind or of a distant storm. It is common practice to call these waves sea and swell, respectively. Sea appears as waves with steep slopes, short crests, and sharp peaks. Individual waves have a wide range of directions, wavelengths, and heights, and may break at their peaks or merge into other waves. Swell, in contrast, is composed of long-crested waves which have a sinusoidal profile and are of uniform wavelength and direction. These swell waves normally do not break, except on reaching a shore or shallow depth. Swell from a distant source is often observed at the same time as a local sea, with the swell waves appearing to pass through the sea wave field, superimposed on it, but with little interaction. All swell must start out as sea in its area of generation. As the wave field propagates across an ocean, it gradually assumes the character normally associated with swell.

Sources of swell in the Pacific

The principal sources of low-frequency swell encountered in the North Pacific can be divided into four classes based on meteorological causes:

a. Extratropical storms in the central North Pacific.

b. The trade winds.

c. Tropical storms, referred to as typhoons west of the international dateline, and hurricanes east of it.

d. Extratropical storms in the Southern Ocean.

Each of these sources generates a low-frequency swell climate with distinctive characteristics that are discussed herein. The purpose of this study is to determine the wave climate due to swell from the Southern Ocean.

North Pacific extratropical storms

The most important swell sources in the North Pacific are the large synoptic-scale storms occurring there. The central North Pacific is notorious as a region of large storms and high waves. The largest single wave (approximately 34 m) reliably observed was recorded in that region by personnel aboard the ship S.S. Ramapo on 7 February 1933 (Kinsman 1965). The largest wave height measured to date in the North Atlantic was 30 m. It was measured by instruments on a buoy located just south of the Scotian Shelf during the Halloween storm of October 1991 (Cardone 1992). The storm systems of the North Pacific move across the northern portion of the ocean from west to east. The storm systems are cyclonic, which means that the eastwardly directed winds are found south of the low pressure centers, which

places them over the ocean. As a result, the North Pacific experiences strong winds over long eastwardly directed fetches for some time before the storm itself actually reaches the west coast of North America. In many cases, the swell waves from a storm will arrive before the storm. This situation is quite different from that encountered off the Atlantic coast of North America where storm waves are those locally generated by strong storms (Northeasters) "breaking out" from the North American continent, such as the Halloween storm of 1991.

The trade winds

The trade wind belt is a region of very steady winds from the east occurring in a region north and south of the Intertropical Convergence Zone (ITCZ), which lies at approximately 5 deg north latitude in the Pacific. This belt extends north and south of the ITCZ for about 15 to 20 deg. The trade winds are part of the ocean atmosphere equatorial system, which transfers solar energy from the oceans where it is absorbed as heat, to the atmosphere and then again to the ocean as kinetic energy in the form of waves and currents. The trade winds are driven by the low pressure in the ITCZ. Although not very strong, the trade winds are very steady and extend over a long fetch. Since trade winds are always from the east, both north and south of the equator, the swell generated always travels to the west. The U.S. coasts affected by trade wind swell are the eastern coasts of the Hawaiian Islands and other Pacific territories.

Pacific tropical storms

Tropical storms in the Pacific may be further classed by their location. They may occur in the eastern Pacific or in the western Pacific (north and south of the equator).

The hurricanes of the eastern Pacific are formed in the tropical Pacific to the west of Mexico. Occasionally, an Atlantic hurricane crosses the Central American isthmus and becomes a Pacific hurricane. In this case, a new name is assigned to the Pacific storm. The storms generally move westward and northward, although some turn to the northeast. It is extremely rare for one to move as far north as southern California and rare for one to hit the Hawaiian Islands. These hurricanes are an occasional source of strong southern swell for California during the late summer and early autumn. WIS report 21 (Tracy and Hubertz 1990) provides hindcast wave information for these hurricanes from 1956-1975. For the Hawaiian Islands, the swell is from the south and east.

In the western Pacific, hurricanes (often called typhoons in this region) are formed in the tropical seas north and south of the equator. Hurricanes cannot form within a few degrees of the equator because of the low Coriolis force there. North of the equator they are found in the area of the Philippines,

ranging as far north as Japan. South of the equator hurricanes are found in the area of New Guinea and the Solomon Islands. Hurricanes both north and south of the equator occur mainly during the late summer in their own hemisphere. Waves from either can reach the shores of the United States when not obstructed by interposed islands.

Southern Ocean storms

The Southern Ocean is the large ocean circling the earth in high southern latitudes. Ice often covers the southernmost portions of this ocean, which borders the Antarctic continent. Strong low-pressure weather systems move from west to east, as in the North Pacific. The strongest systems are cyclonic, low-pressure centers, which in the Southern Hemisphere have a clockwise circulation. The winds over the Southern Ocean blow mostly from the west and are often of gale force (14 to 28 m/s) or higher. This, combined with the extremely long fetches possible, since the ocean completely encircles the globe, makes high seas and swell very common. Due to the earth's spherical shape, waves propagating to the northeast in portions of the Southern Ocean, such as south of Australia and New Zealand, can eventually reach the North Pacific after traveling along great circle paths (Figure 1). Swell from this area is known to propagate long distances throughout the world's oceans (Barber and Ursell 1948).

Swell in southern California

The Southern California Bight (the coastal area from Point Conception south to Mexico) is a region for which swell from the south is of special interest. During the northern winter, most swell is from the North Pacific, although the northwest-southeast orientation of the coast, and presence of large islands immediately offshore, protect much of the region from this source. During the northern summer, the dominant swell is often from the south. This is the hurricane season in the eastern North Pacific, and also the Southern Hemisphere winter. These sources of swell dominate in the absence of large swell from the North Pacific. This location is more exposed to Southern Hemisphere swell than are sites farther north along the U.S. Pacific coast. In particular, it is far enough south to be exposed to large areas of the Indian Ocean through the gap between New Zealand and Antarctica.

High population density and high land values around the Southern California Bight make it a region of great interest to coastal engineers. Erosion of beaches and bluffs by waves is a matter of great public concern. Studies of wave refraction in the region were conducted by Munk and Traylor (1947), O'Brien (1950), and more recently by O'Reilly (1993). Measurements of swell were conducted by Wiegel and Kimberley (1950), Munk and Snodgrass (1957), Munk et al. (1963), and Snodgrass et al. (1966). These measurement studies attempted to relate measured swell at a site to weather events in the Southern Hemisphere by estimating travel distances based on
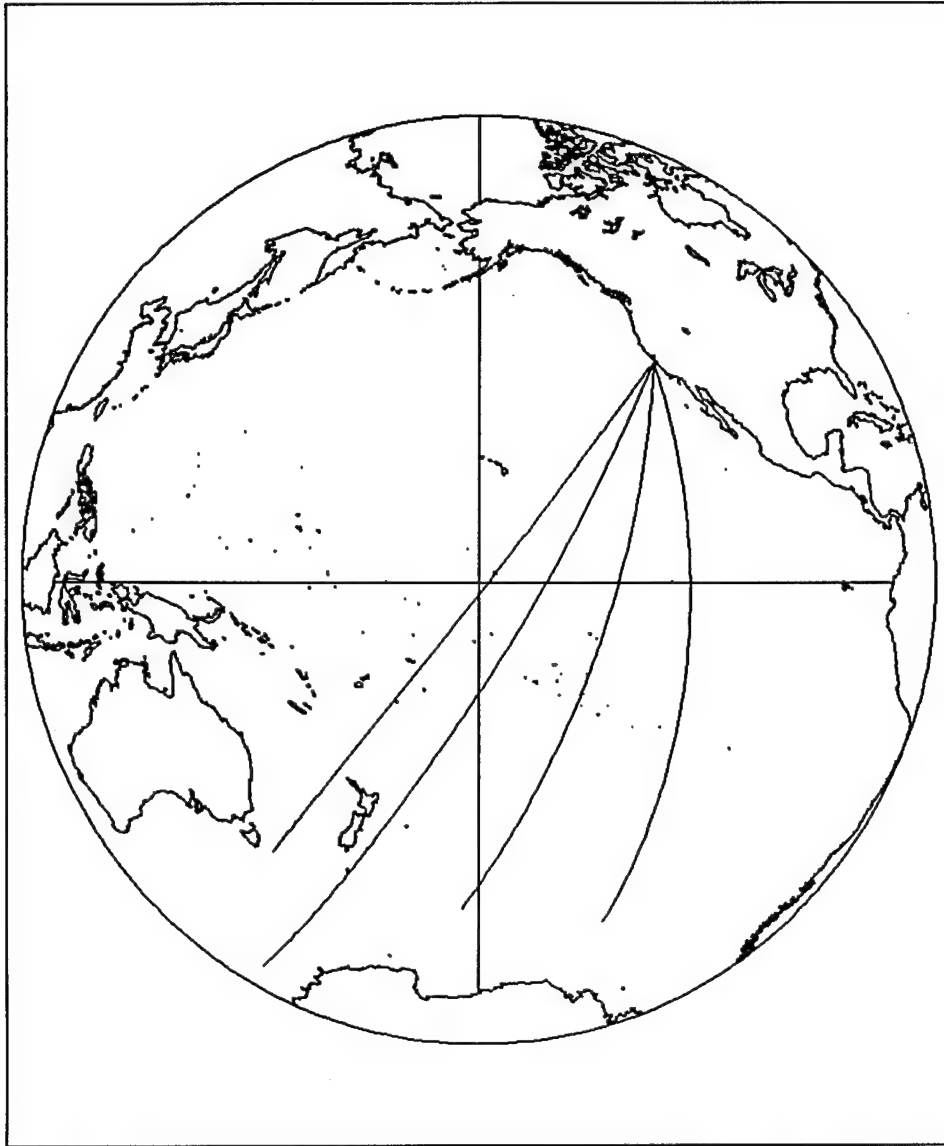
Figure 1. Example great circle paths of Southern Hemisphere swell from
source region to the U.S. west coast

arrival times of different frequencies and their group velocities. These
methods have been used by contemporary forecasters to infer the arrival of
swell based on the time, strength, and location of storms in the Southern
Ocean.

To date, the definitive study of Southern Ocean swell in the Pacific was
done by Snodgrass et al. (1966). Swell from storm events was tracked across
the Pacific using wave gauges in New Zealand, American Samoa; Palmyra
Island; Hawaii; the mid North Pacific; and Yakutat, Alaska. The study
evaluated the ability of various wave mechanisms to produce the observed
data. The effects considered were geometric spreading, dispersion, blocking,

and scattering by intervening islands, and wave interaction effects. These wave interaction effects result in the transfer of energy from one frequency and direction combination within the spectrum to another. The resulting observable phenomena can be described as wave dissipation, frequency shifting, beat formation, and self-scattering. For narrow-band wave trains with periods over 13 s, the authors found that the observations were explainable in terms of energy propagation on a spherical earth (oblateness ignored), with frequency dispersion, no energy loss, no interaction with the ambient wave fields, and simple shadowing by interposed land bodies. These effects are modeled in this study.

2 Theory

Wave Spectrum

Wave conditions at a given point (x,y) and time (t) may be described by a function $F(x,y,t,f,d)$, the wave spectrum, where f refers to the different frequencies of waves present, and d to the different directions. The function F has units of square meters per second per radian. It is defined such that the sea surface variance attributable to waves with frequencies between f_0 and f_1 and directions between d_0 and d_1 is given by $\int\int F(x,y,t,f,d)\ df\ dd$.

When wave energy travels from one location to another, it travels along certain paths. These paths are referred to as rays and are extremal in the sense that they represent the shortest or longest distances between points. For a spherical surface, such as the earth (neglecting oblateness), the paths are the great circle arcs connecting the two points. A great circle is the line formed by the intersection of the earth's surface and a plane passing the center of the earth. If two locations are at antipodes (opposite points on a diameter of a sphere), there will be an infinite number of great circles which could pass between the two points. Great circle propagation paths are only valid for a homogeneous medium, in which there is no refraction. For the case of wind-generated swell, the open ocean is deep enough that refraction is negligible, except when the waves approach land or regions of shallow water. This is not the case for some waves such as tsunamis, for which all the ocean is shallow. Refraction may also occur when waves pass through regions of relatively strong currents. These effects are smaller for longer period waves, such as swell, than for sea.

As energy travels along the great circle path, F (energy density) will be conserved in the absence of energy gains and losses. This may seem at first to contradict the recognized effects of frequency dispersion and geometric spreading of wave energy, but one should note that what is conserved along ray paths is wave energy density, not wave energy. Wave energy appears only when energy density is integrated over angle and frequency ranges dd and df. The optical analog of water-wave energy density is luminance, which does not decrease with distance unless light is absorbed. For example, a distant star

has the same luminance as a closer star such as the sun, but the earth receives less light from the distant star since it subtends a smaller angle. Likewise as an observer moves farther from a source region of swell, the angle subtended by the source becomes smaller, and the integral of energy density over that angle becomes smaller. When an observer moves past a distance of one quarter of the earth's circumference, the subtended angle begins to increase again until the antipode is reached. Because the earth is nearly spherical, rays emanating from a point initially diverge, but then converge again.

Dispersion

"Dispersion" is a phenomenon occurring in media for which the wave speed varies with frequency. Surface gravity waves are dispersive, with the group speed c_g, the speed at which wave energy travels. The group speed is given by $c_g = g/2\omega$, where g is the acceleration of gravity. The lower the value of ω, the angular frequency, ($\omega = 2\pi f$) the faster wave energy travels. This equation is valid for waves which have short wavelengths compared with the water depth, which is the case for swell in the deep ocean. The practical effect of dispersion is that waves generated simultaneously in a distant source region will arrive at different times at a location, with the low-frequency waves arriving first, and the higher frequency waves arriving later. For waves traveling across an ocean, the arrival times can be spread over a period of many hours or days. As a result of this frequency spreading, the spectrum of waves arriving at the point of observation will exhibit a narrow peak which shifts slowly to higher frequencies. The rate of shifting is a measure of the degree of dispersion and can be used to estimate the distance of the generating event (Barber and Ursell 1948). An example of this is illustrated later, in the hindcast results of a hypothetical storm, by the decrease in mean period with time. Dispersion accounts for the mono-chromatic character (narrow spread of energy density in frequency space) of swell from distant storms. It also reduces the energy of the wave at a point at any time. Since energy is the integral of energy density over a frequency range, and since the range of frequencies originally present has been reduced, the energy present at a given time is reduced.

3 Measurements

Wave-measuring instruments respond to all changes in the water's surface regardless of frequency and direction. Thus, the results must be analyzed in some manner to isolate a particular component of the wave climate. In this case the component is swell arriving from the Southern Hemisphere. The frequency and direction bands used to define southern swell are subjective. Southern swell cannot be measured directly but must be defined as a portion of the spectral information available. The best measurements available for analysis in this study are from buoys.

Data from Buoys

The National Data Buoy Center (NDBC) of the National Oceanic and Atmospheric Administration (NOAA) has operated an offshore buoy measurement program since the 1970's. NOAA directional buoy wave records are available beginning in May 1986. Although directional buoys were operational on the California coast prior to 1986, the earlier records were not archived.

Initially, data from two directional buoys, 46042 (36.8N, 122.4W) and 46125 (33.7N, 119.1W), were examined to identify swell from the Southern Hemisphere. Measurements from other buoys are available in the region but do not include directional information. Buoy locations are shown in Figure 2. The years 1988 and 1989 were chosen for analysis since both buoys were operational during the Northern Hemisphere summers of those years. Results from one or the other of the two buoys were not available during the summer months of 1986, 1987, 1990, 1991, and 1992. First, the data were examined to determine all times when the frequency spectra were available. Data records are potentially available every hour. Next, those times were eliminated when a hurricane or tropical storm was present in the Northeast Pacific. This was done so that hurricane swell arriving at the coast from the south would not be confused with swell from the Southern Hemisphere.

The remaining data were analyzed on the basis of where southern swell energy would be located in frequency and direction within the spectra. The measured spectral information was subsampled to obtain only that energy
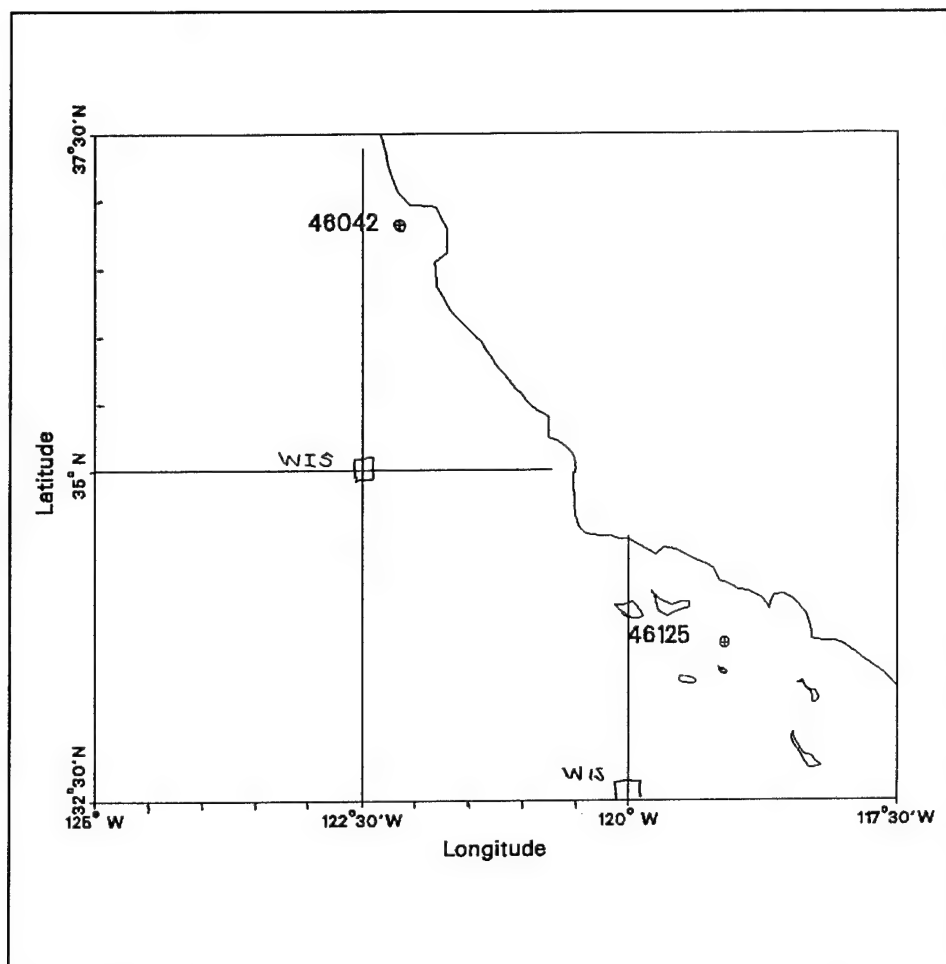
Figure 2. Location diagram for buoys 46042 and 46125

density with periods greater than or equal to 12.5 s. These bands have mid-band frequency values of 0.03, 0.04, 0.05, 0.06, 0.07, and 0.08 Hz, with corresponding periods of 33.3, 25.0, 20.0, 16.7, 14.3, and 12.5 s, respectively. Next, a direction was assigned to each of these frequency bands based on the information in the National Oceanographic Data Center (NODC) records.

Analysis of Data

Two direction estimates for each frequency band are provided based on calculations using the quad- and co-spectra derived from motions of the buoy. The first (alpha-1) is referred to as a mean direction for the particular frequency band and the second (alpha-2) as the principal direction (Steele 1992). Neither of these names, "mean" and "principal," has any physical significance. If the two estimates are within 15 deg of each other, there is likely only one direction for the particular frequency. This value of 15 deg is subjective and based on the premise that crossing seas at the same frequency would be more than 15 deg apart in direction. At the peak of the spectrum,

the two estimates usually agree within 15 deg 99 percent of the time.[1] If the estimates differ, there could be two wave trains of the same frequency, but from different directions. In this case, neither direction is considered an accurate representation. The population of southern swell waves was further subsampled to contain only those cases where the two directional estimates for each frequency band agreed within 15 deg, and the value of alpha-1 was between 135 and 235 deg. There were few measured data left to examine in the population when both these criteria were imposed. Thus, the requirement that alpha-1 and -2 had to be within 15 deg of each other was removed, and the mean of the two estimates was chosen as representative of that frequency band if both were within the directional window 135 to 235 deg, and the energy density exceeded 0.2 m^2/Hz (0.17 m). This lower limit on wave energy was imposed since the buoy response becomes less accurate for low-frequency and low-amplitude waves.

The differences between alpha-1 and -2 for all six frequency bands were examined to determine their distribution under these conditions. Typically about 75 percent of the differences were less than 20 to 25 deg. An example for August 1988 is shown in Figure 3. Thus, it is assumed that even if alpha-1 and -2 differ by more than 15 deg, their mean probably represents an approximate estimate of swell direction from the directions between 135 and 235 deg most of the time.

This resulting set of data is defined as swell arriving from the Southern Ocean. The energy density (square meters per hertz) was converted to a swell wave height by multiplying the energy density in each frequency band by the bandwidth (a constant 0.01 Hz in this case), summing over all bands, taking the square root of the sum, and multiplying by 4. A single wave period and direction were determined from the energy weighted means over the six frequency bands.

The energy density in the six frequency bands was examined to determine the correlation of values at the two buoy locations. Figure 4 is a scatter diagram of energy density within the frequency bands 0.03 to 0.08 Hz from 12-15 September 1988 measured by buoys 46042 and 46125. The direction, in this case, is one where alpha-1 and -2 agree within 15 deg and both lie between 135 and 235 deg. Thus, only data meeting the more stringent directional criteria are used for this analysis. This data shows a tendency for some energy density estimates to be higher at 46042 than at 46125. This difference is attributed to sheltering from Santa Barbara and San Clemente Islands and the shoal areas of Osborn, Tanner, and Cortes Banks. Sheltering of wave energy from islands and shoals off southern California is a separate problem and not within the scope of this study. Thus, it was decided not to attempt comparisons of deepwater, unsheltered-model results to the measured

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[1] Personal Communication, 1993, David Wang, National Oceanographic Data Center, Stennis Space Center, Mississippi.
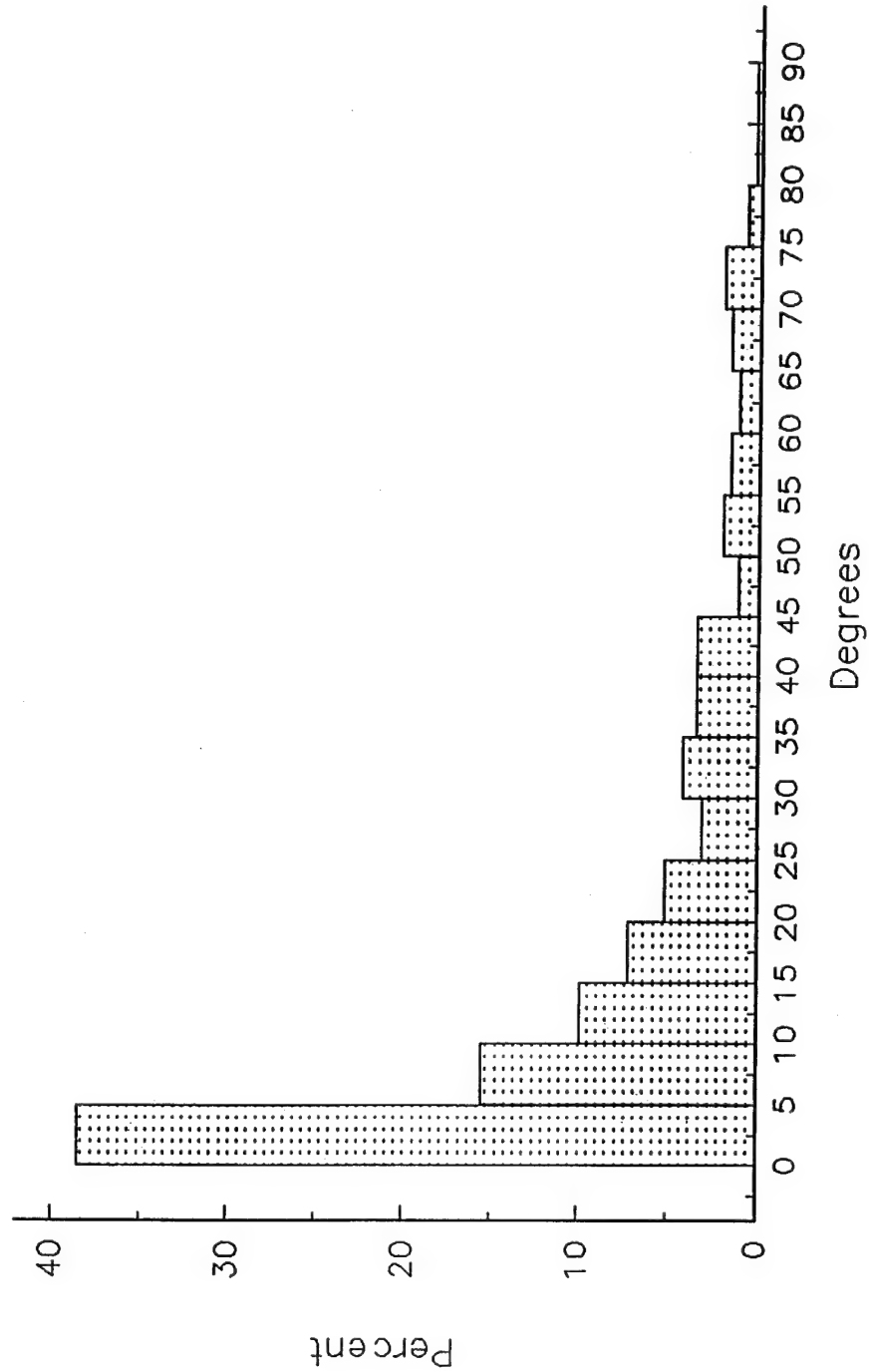
Figure 3. Percent distribution, by 5-deg intervals, of the difference between angle estimates in the first six frequency bands of buoy data

data from buoy 46125 and to concentrate on the unsheltered results from 46042.

Data from buoy 46042 were processed as described above for June-September 1988 and May-July 1989. Wave height, mean period, and mean direction results for these periods are shown in Figures 5 and 6, respectively. Accepting the admittedly subjective definition of Southern Hemisphere swell, and assuming that the occurrence of swell in these two summer periods is typical, the characteristics of southern swell can be described as follows.

Heights are limited to a maximum of about 1 m. There are definite events when heights increase and then decrease in a symmetrical manner. Duration of these events is from about 100 to 200 hr or 4 to 8 days from beginning increase to ending decrease. Variation about the mean signal is generally less than 0.5 m. Mean periods range between 12.5 and 20 sec. The 12.5-sec period corresponds to the highest frequency band included in the analysis. Most periods are included in the bands between 13 and 17 sec. The events noted in the swell heights are also apparent in the mean periods. Mean period will increase and then decrease corresponding in time and duration to the height signal. Variation about the mean signal is about 1 to 2 s. Mean directions are confined to the band 135 to 235 deg by the analysis, and are generally between 150 and 220 deg or a 60- deg window centered at 180 deg. The event signature of the directional signal tends to be a reduction in variation of the signal and concentration about a narrower directional spread. Table 1 summarizes some statistics of the height, mean period, and mean direction as defined above from analysis over the two summers.

Table 1 Summary Statistics for Measured Southern Swell Buoy 46042, 1988 and 1989						
	Height, m		Period, sec		Direction, deg	
Statistic	1988	1989	1988	1989	1988	1989
Minimum	0.1	0.1	12.5	12.5	140	139
Maximum	1.0	1.1	22.5	20.9	235	232
Mean	0.4	0.4	14.5	14.6	190	178
Median	0.4	0.3	14.3	14.3	190	178
Std Deviation	0.2	0.2	1.3	1.3	14	15
No. of Obs.	1993	1411	2003	1434	2003	1434

The goal of hindcasting southern swell is to match, for example, the signals in Figures 5 and 6, and obtain statistics similar to those in Table 1. Swell from the Southern Ocean will accurately be represented along the U.S. Pacific coast for coastal engineering studies if this is achieved.
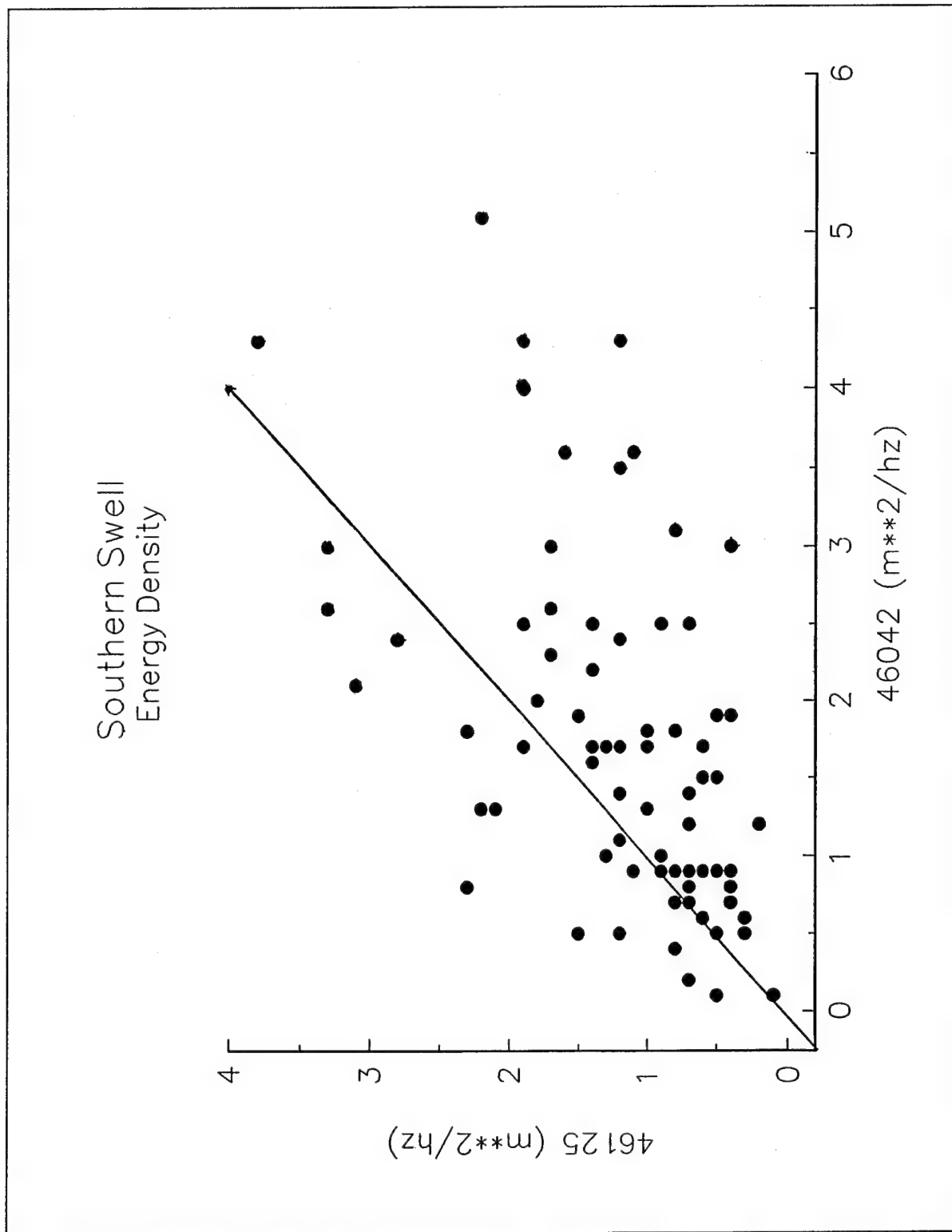
Figure 4. Scatter diagram of energy density from the first six frequency bands of buoys 46125 and 46042
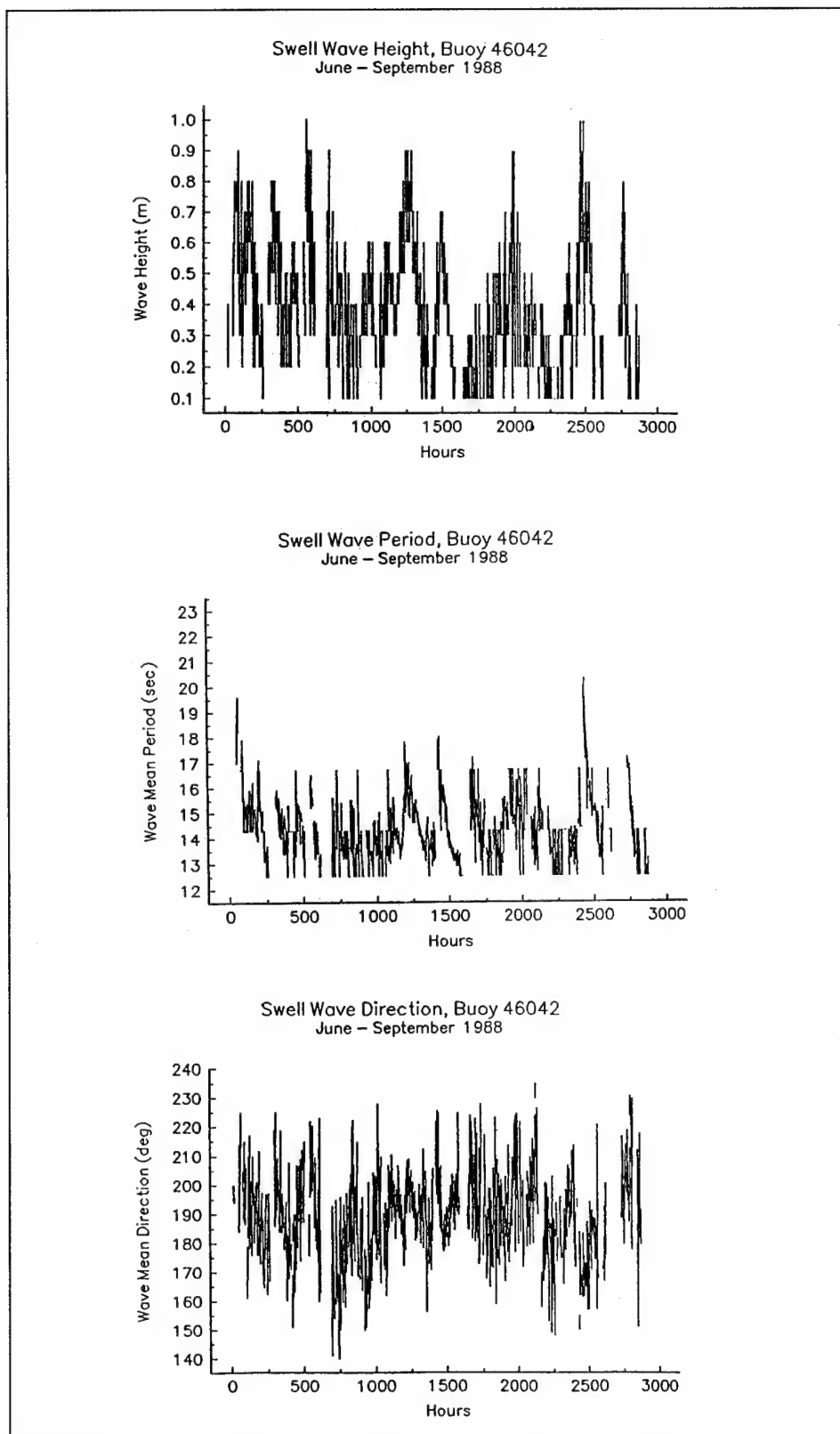
Figure 5. Swell height, mean period, and mean direction from buoy 46042 for
the period June - September 1988
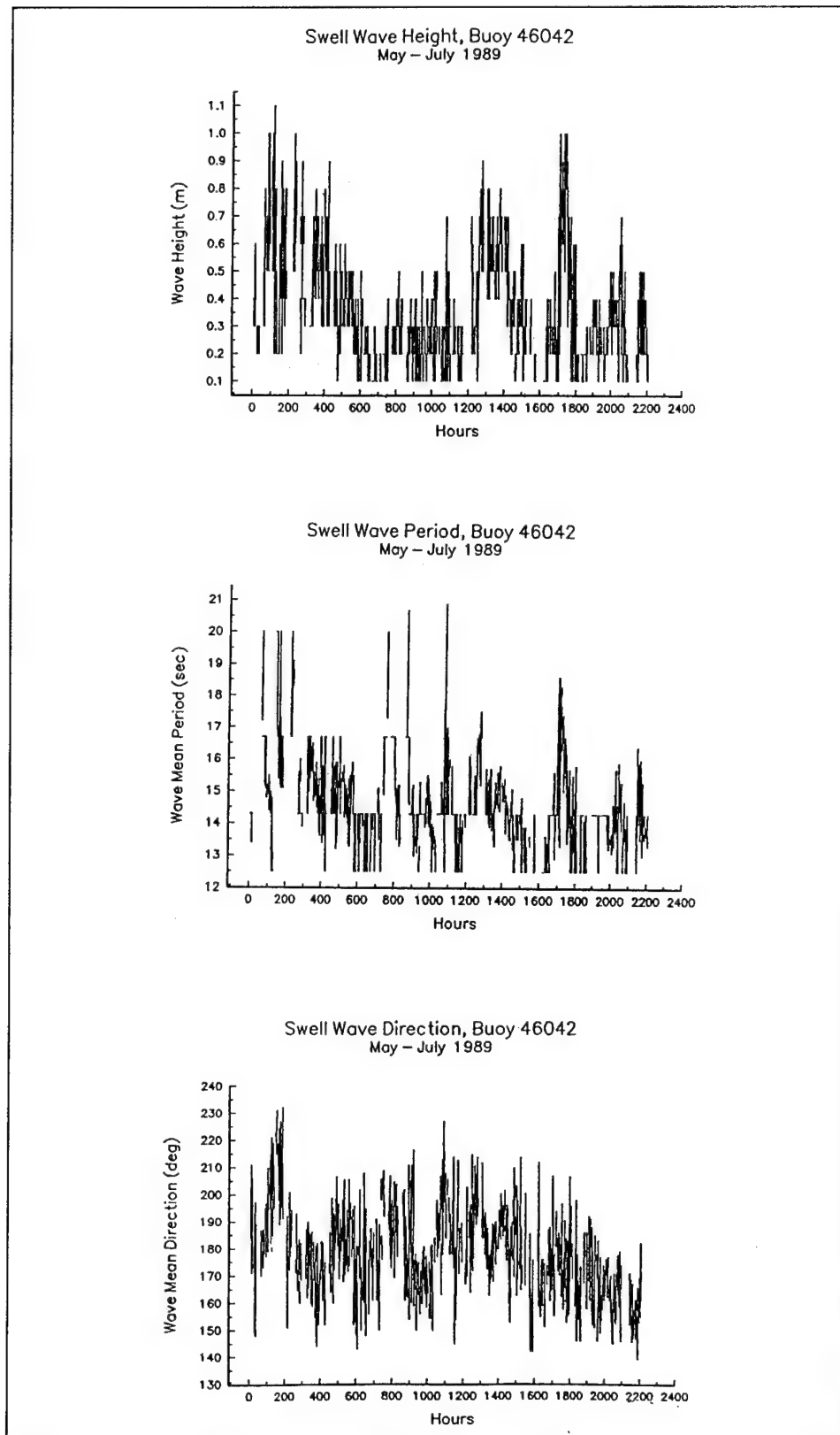
Figure 6. Swell height, mean period, and mean direction from buoy 46042 for
the period May - July 1988

4 Hindcast Model

WISWAVE version 2.0 (Hubertz 1992) is the current numerical model used by the U.S. Army Corps of Engineers to generate wave information along U.S. coastlines. It is a discrete spectral wave model that calculates energy in a matrix typically containing 16 direction bands and 20 frequency bands. The model was developed by Dr. Donald T. Resio and is described in Resio and Perrie (1989). It was used to hindcast 32 years (1956-1987) of wave conditions on each of the Great Lakes (Hubertz, Driver, and Reinhard 1991), to revise wave information along the Atlantic coast for the period 1956-75 (Hubertz et al. 1993), and for numerous site-specific projects studied at CERC.

The model solves the spectral energy balance equation

$$\frac{\partial E(f,\theta)}{\partial t} + \frac{\partial cc_g\, E(f,\theta)}{\partial x} + \frac{\partial cc_g\, E(f,\theta)}{\partial y} = S_{at} + S_{nl} \quad (1)$$

where

E = spectral energy density

f = frequency of spectral component

θ = propagation direction of spectral component

t = time

c = phase speed of spectral component

c_g = group velocity of spectral component

x,y = plan-view spatial coordinates

S_{at} = atmospheric energy input from the wind

S_{nl} = transfer of energy through frequencies due to nonlinear wave-wave interactions

Grid and Input Options

A grid of latitude and longitude lines (67 by 55) with 2.5-deg spacing was developed for use in this series of hindcasts. The grid (Figure 7) covers essentially the entire Pacific Ocean basin to allow southern swell generated in the Southern Ocean to propagate to the Northern Hemisphere.

Model input options are listed in Appendix A and explained in Hubertz (1992). A matrix of values defining whether a grid point is land (0) or water (1) is contained in the options file. A subjective representation of islands in the South Pacific is shown by the land points (zeros) in the lower half of the grid. The center frequencies associated with each of the 20 frequency bands are 0.03, 0.04, 0.05, 0.06, 0.07, 0.08, 0.09, 0.10, 0.11, 0.12, 0.13, 0.14, 0.15, 0.16, 0.17, 0.18, 0.19, 0.20, 0.21, and 0.22 Hz. Wave periods corresponding to the frequencies are 33.3, 25.0, 20.0, 16.7, 14.3, 12.5, 11.1, 10.0, 9.1, 8.3, 7.7, 7.1, 6.7, 6.2, 5.9, 5.6, 5.3, 5.0, 4.8, and 4.5 s, respectively.

Hypothetical Storm Test

Since the southern swell signal is generally small and difficult to isolate from all the other wave energy present in the ocean, it was decided to first test a situation where only wave energy from a typical Southern Ocean storm is present. This is a hypothetical situation since wave energy is always present from possibly many different weather systems on this large a scale. In a typical Southern Ocean storm, the general atmospheric circulation south of 40° S is from west to east. This zonal flow is dynamically unstable, which means that latitudinal perturbations of the flow result in formation of cyclones. These systems of clockwise circulation (opposite direction from the Northern Hemisphere) move in the zonal flow from west to east. Sub-Antarctic cyclones tend to be stronger and larger in geographic extent than their Arctic counterparts due to the distribution of land, sea, and ice in the two different regions. Typical storms can have radii of hundreds of nautical miles and maximum wind speeds on the order of 50 knots.[1]

The hypothetical storm chosen for the test is a stationary symmetrical cyclone centered at 50° S, 170° W with a radius of four grid points (600 nm) and is shown schematically in Figure 7. Wind speeds are zero everywhere except as indicated by the vectors in Figure 7. The magnitude, or wind speed, of each vector is the same. Wind speed at each vector is increased in magnitude from 10 knots during the first day, to 20 knots during the second, to 30 knots during the third, and to 40 knots during the fourth day. Wind speed is then decreased in the same manner.

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[1] A table of factors for converting non-SI units of measurement to SI units is presented on page vii.
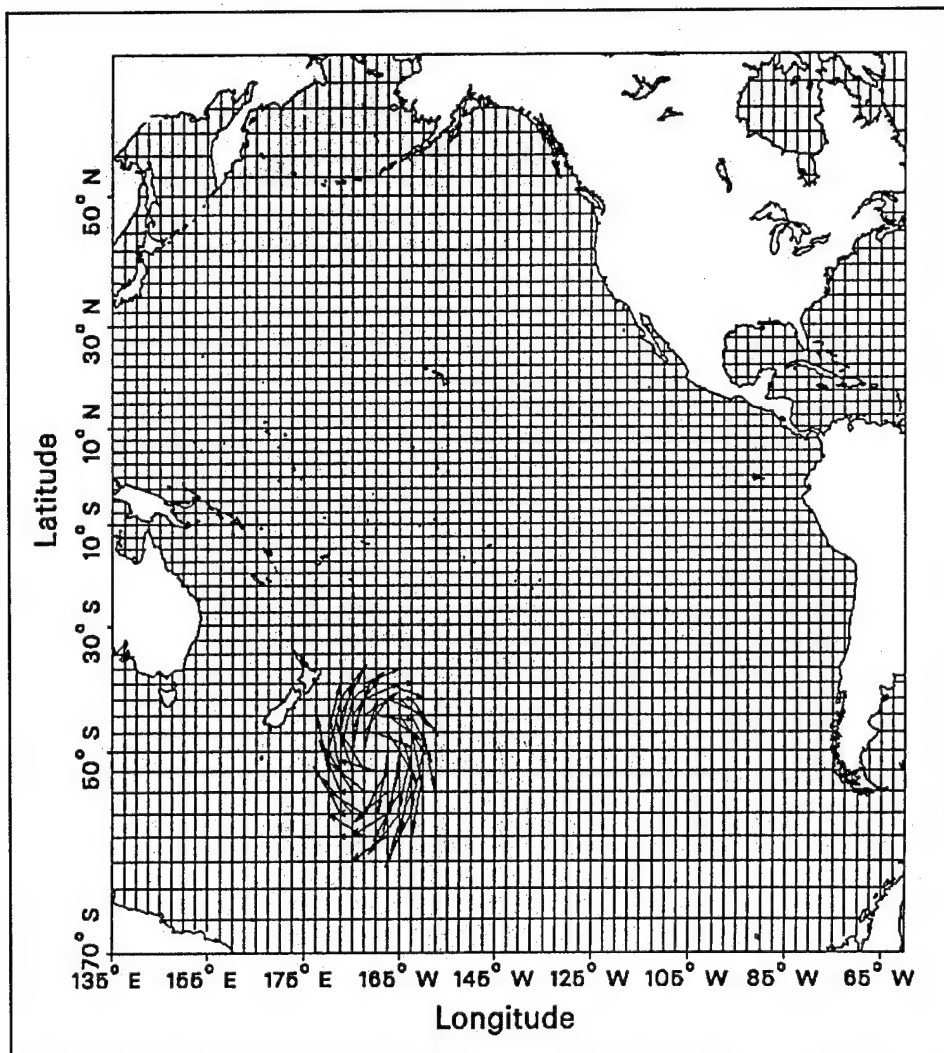
Figure 7. Numerical model grid with wind vectors depicting hypothetical storm off the southeast coast of New Zealand

Model results are output every 3 hr at the grid point (42,43) [(1,1) is located in the lower left corner] located at 35° N, 122.5° W. Wave spectra are processed in the same manner as used for the buoy data. That is, the mean direction in each of the first six frequency bands is examined to determine if it is within the range of 135 to 235 deg. Energy in those bands satisfying this condition is summed and expressed as a swell height. An energy-weighted mean period and direction are then calculated from those bands. Swell height, mean period, and mean direction for the hypothetical storm are shown in Figure 8.

Swell height builds and decays consistently with the increase and decrease of wind speeds in the storm. Note that only those winds blowing toward the United States will contribute to wave energy arriving at the output station. The magnitude of swell height is consistent with observations. The maximum
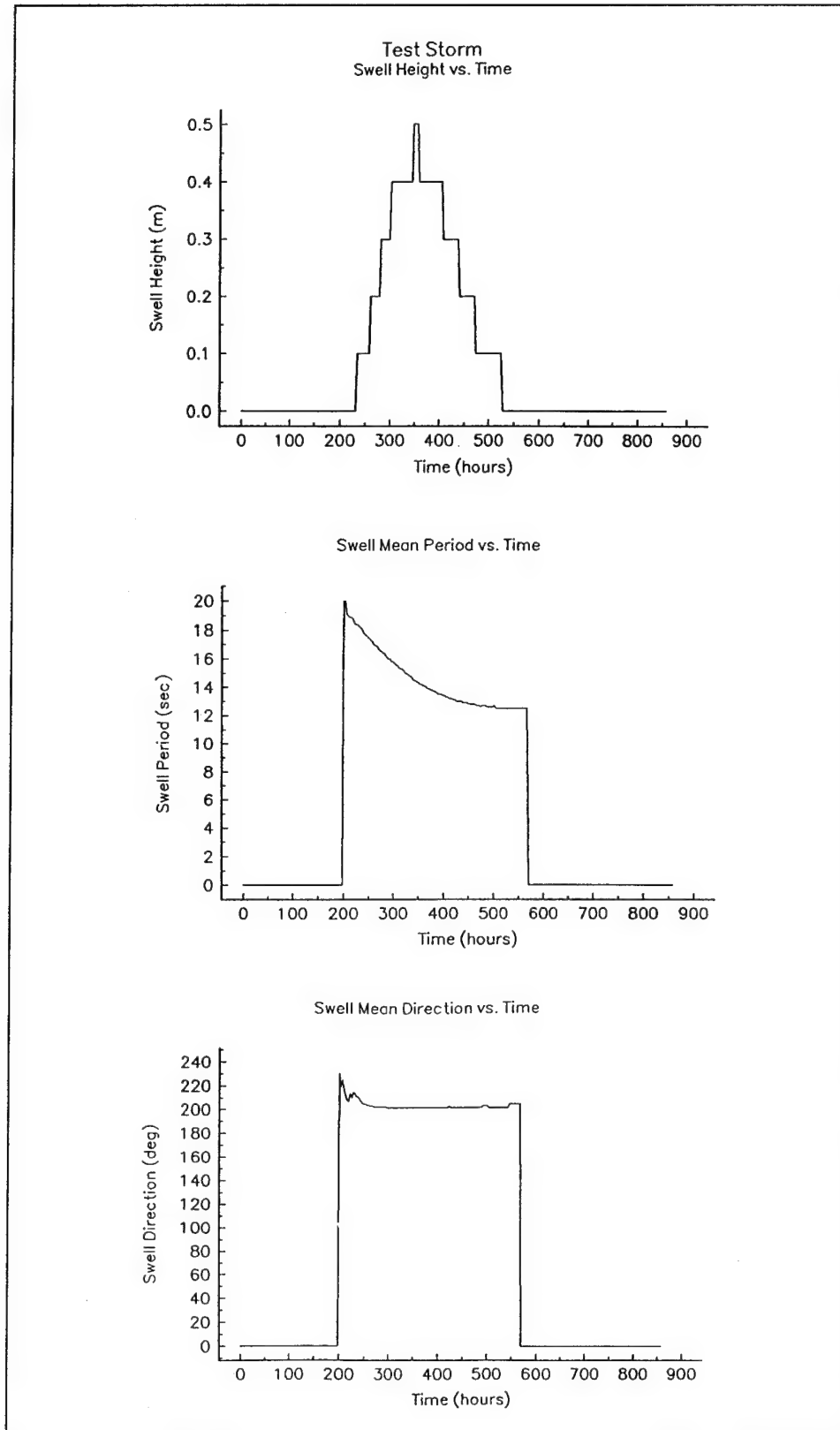
Figure 8. Swell height, mean period, and mean direction from hindcast of
hypothetical storm

value of 0.4 to 0.5 m agrees with the means in Figures 5 and 6. The distance from the source to the output station is given by

$$d = r \cos^{-1} (\sin a \sin b + \cos a \cos b \cos c) \qquad (2)$$

where

> r = radius of the earth, taken as 6,372 km
>
> a = latitude of the station
>
> b = latitude of the source
>
> c = difference in longitudes between source and station

For the simple case of a great circle, along a line of longitude from the equator to the North Pole, a = 90 deg, b = 0 deg, and c = 0 deg. Thus $d = r \cos^{-1}$ (sin 90 sin 0 + cos 90 cos 0 cos 0) or $d = r \cos^{-1}$ (0) or 1.57 radians times r. This is π r/2 or one fourth the circumference of the earth (2 π r/4). For the case of the station off the California coast and the source region in the Southern Hemisphere, a = 35 deg, b = -50 deg (negative in Southern Hemisphere), and c = 45 deg (170 to 125 deg). These values result in a great circle distance of about 10,400 km. Wave energy travels at the group velocity (g/4 π f) which for f = 0.05 hz (20 s) is about 15.6 m/s. Thus, a 20-sec swell departing the location of the storm should arrive at the observation station about 8 days later. This is what the model results in Figure 8 indicate. Mean periods decrease with time, indicating successively later arrival of higher frequency wave energy traveling at slower speeds. Using the arrival angle of 203 deg at the observation station to backtrack the wave energy, 10,400 km accurately locates the storm. It is concluded from these results that the model is producing results consistent with observations of this phenomenon. Next, a hindcast was performed for the summers of 1988 and 1989 when directional information was available from buoy 46042 off the coast of central California.

Wind Input

Input winds for WISWAVE were obtained from the Navy's Fleet Numerical Oceanography Center (FNOC). These global wind fields, available at a spacing of 2.5 deg latitude, longitude and elevation of 19.5 m, were input to the model at 6-hr intervals. The winds are produced using a numerical model of the atmosphere, observations of meteorological parameters on a global basis, and from satellite observations. Wind fields at 0000 and 1200 universal time coordinate (UT) are based on observations and analysis, and represent initialization information for the atmospheric numerical models. Wind fields at 0600 and 1800 UT are model predictions from the initial states at 0000 and 1200 UT, respectively.

An example of the winds over the Pacific Ocean is shown in Figure 9. The length of the vectors is proportional to wind speed, and the arrow head
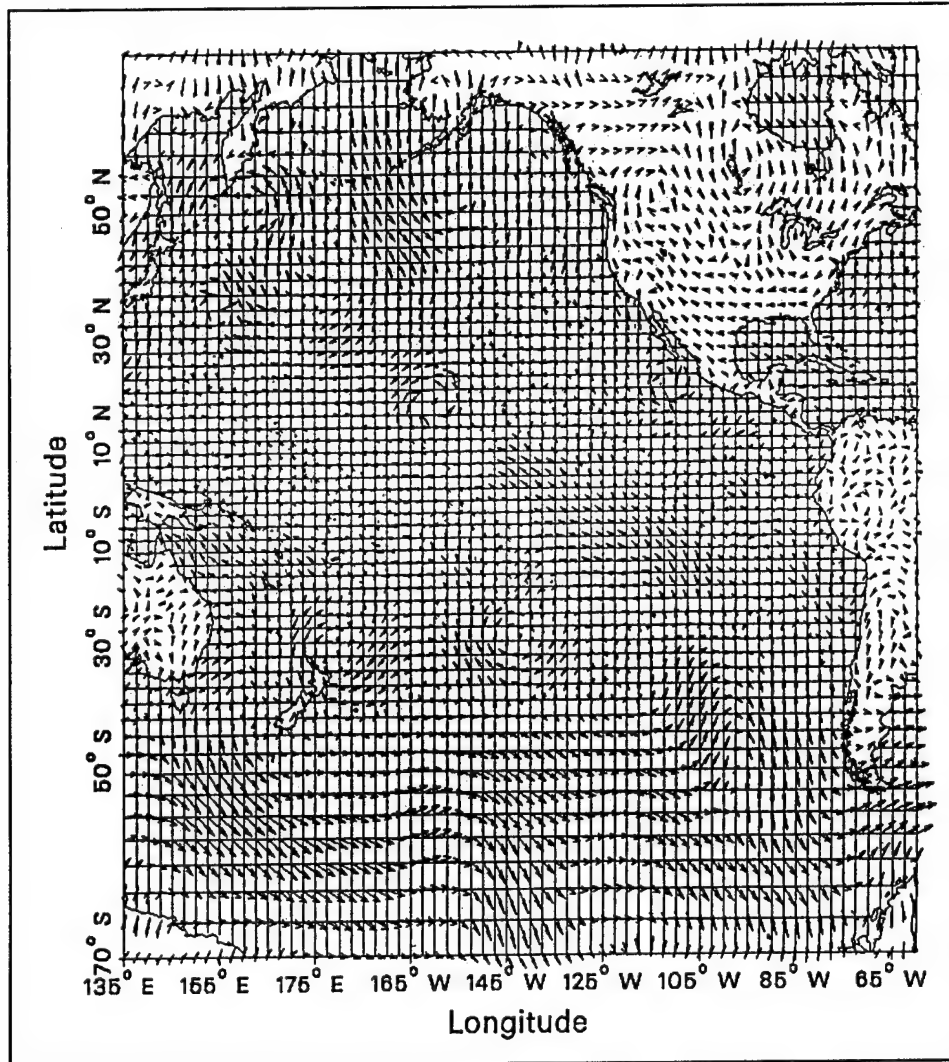
Figure 9. Wind vectors over numerical grid illustrating example of various weather systems over Pacific Ocean

indicates the direction toward which the wind is blowing. It is obvious from the patterns in the vector field that multiple weather systems can produce wave energy along the U.S. Pacific coast. For example, the winds blowing from the northwest off the southern California coast will generate local waves. The cyclonic winds centered at 17.5° N, 160° W and winds from the northwest in the northwest Pacific may produce swell. Hurricane Kirsty just evident southwest of Baja Mexico could produce swell from the south if it moved on a track to the northwest. The strong winds in the Southern Ocean blowing toward the northeast are typical of the winds which produce southern swell.

5 Results

Time periods for study were selected on the basis of availability of directional buoy data, the absence of eastern North Pacific hurricanes, and the presence of strong weather systems in the Southern Ocean, as observed on wind vector plots and surface atmospheric pressure charts. Daily wind vector plots, such as Figure 9, were produced for time periods to display Southern Hemisphere storms as well as weather systems in the Northern Hemisphere.

The same model options file was used as used for the hypothetical storm. As stated above, southern swell on the U.S. west coast can result from tropical storms and hurricanes off the coast of Mexico, as well as from distant storms in the Southern Hemisphere. In this study of Southern Hemisphere swell, time periods dominated by eastern North Pacific hurricanes were not hindcast. Records from Mariners Weather Log indicated that, for most dates in June, July, and September 1988, and May, June, and July 1989, southern swell from nearby hurricanes would not be present. All months listed were hindcast in their entirety with 10 days of winds leading into the period for spin-up of the model.

Wave height, period, and direction comparisons were made using data from the model grid point at (35.0° N, 122.5° W) and NOAA buoy 46042 (36.8° N, 122.4° W) for the 6 months hindcast. Values are compared every 3 hr. Wave heights, mean periods, and mean directions from the buoy data were determined as described above. Hindcast values were determined in the same way. These comparisons are presented in Figures 10 and 11 as plots of these parameters for each year hindcast.

Comparison of Height, Period, and Direction

Swell heights agreed with measured values some of the time, but tended to be generally larger (by about 0.5 m) and at times exceeded values derived from the measurements by more than a meter. Mean periods from the hindcast and measurements tended to vary within the same limits and showed some correlation to each other related to increases and decreases in swell height. Mean swell direction from hindcast and measurements agreed some of the

Figure 10. Comparison of measured and hindcast swell height, mean period, and mean direction at buoy location 46042 during June - September 1988

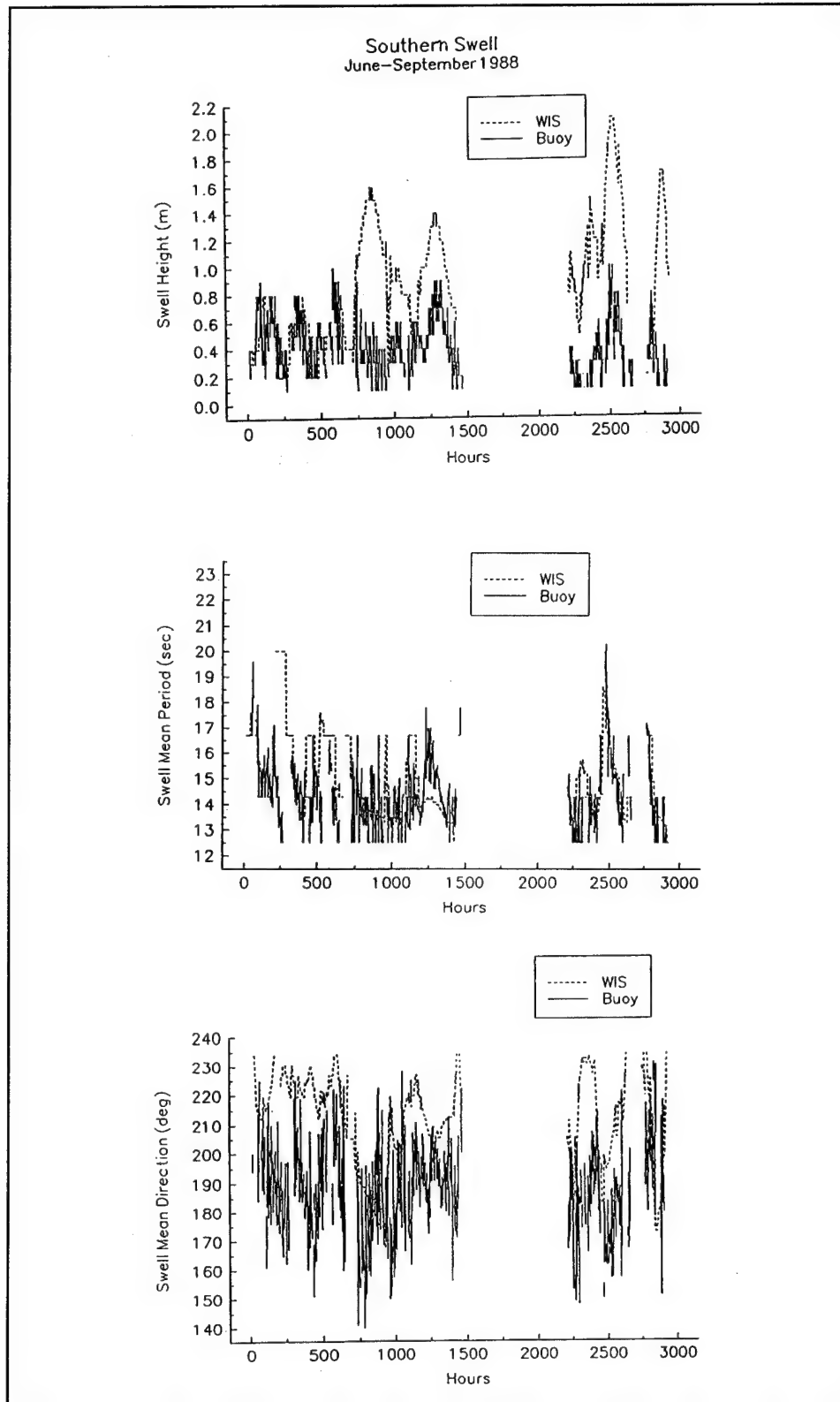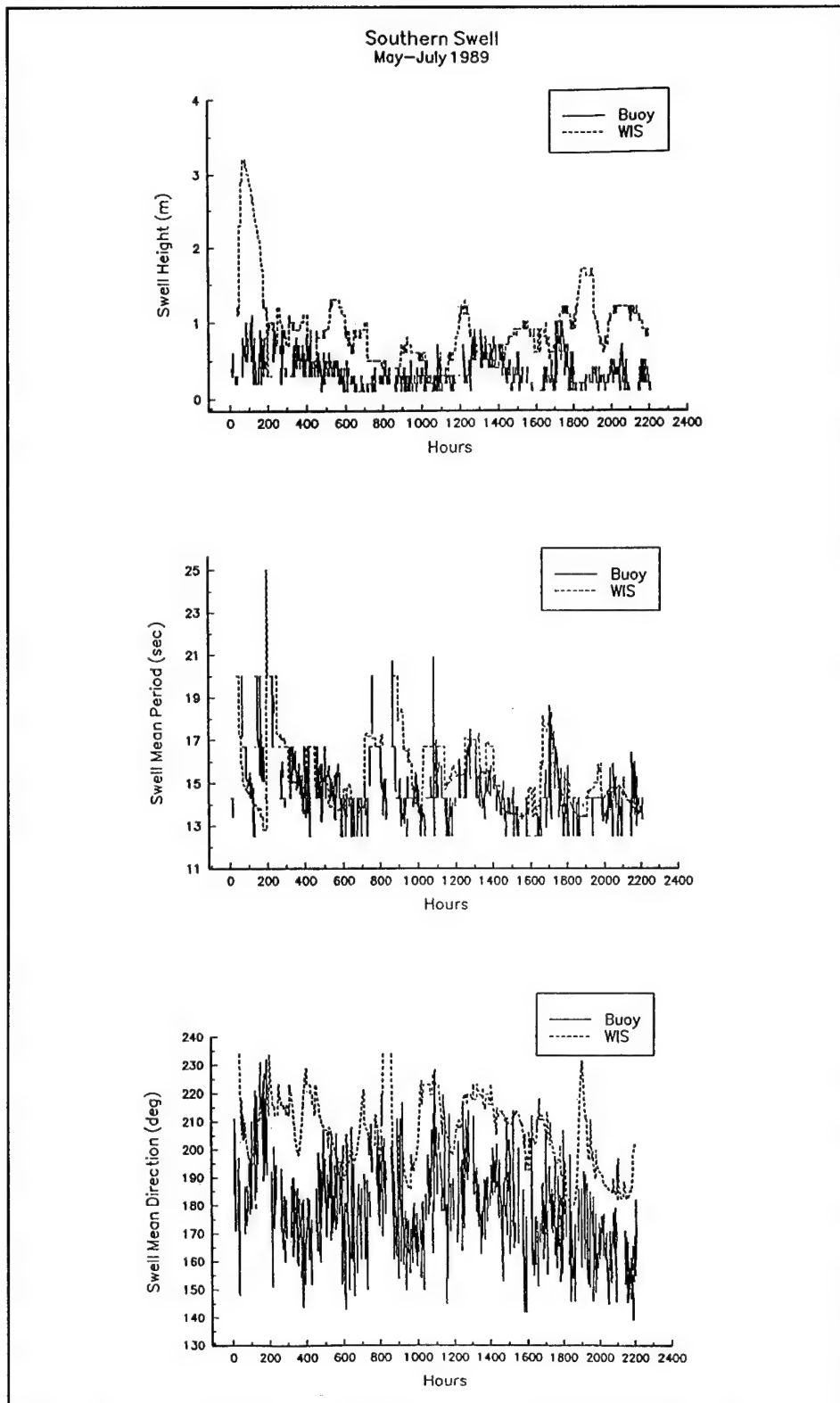Figure 11. Comparison of measured and hindcast swell height, mean period, and mean direction at buoy location 46042 during May - July 1989

but hindcast values tended to be larger (by about 30 deg). Directions were defined in the compass sense.

There are several explanations for the differences in swell height and direction noted above, but at this time none can be proven as the cause. For example, the definition of swell height and direction used herein is subjective and may not be accurate. Energy in this part of the spectrum is small and usually displaced from the peak. Thus, directions based on values of alpha-1 and -2, which do not agree within 15 deg, may be ill-defined. It is known that buoys such as 46042 do not respond as well to low-energy and low-frequency waves as they do to higher energy and higher frequency waves.

Winds in the Antarctic region are derived without the benefit of as many observations as in more populated and heavily traveled regions. Thus, there is more uncertainty in speeds and directions. Any errors in these values readily translate to errors in wave height, period, and direction.

The effect of the many islands and shoals in the South Pacific on swell heights and directions as the energy propagates to the north is unknown. The subjective designation of land points in the numerical grid to represent these features may not be correct, but there is no way to know at this time. Only the propagation of wave energy is affected by designating these land points. Energy is not dissipated by swell breaking on shoals or shorelines as naturally occurs. No attempt is made to reduce the energy density propagating past these islands due to these effects.

An attempt is made to distinguish possible errors in winds from effects of propagation through intermediate islands by examining measured data at a location which should not be affected by the islands. If hindcast results are too high at this location with respect to measured estimates, the cause would not be related to energy loss by passage through islands and shoals. Nondirectional wave measurements are available from NOAA buoy 32302 at 18° S latitude and 85.1° W longitude (approximately parallel to the border between Peru and Chile). Data from this buoy were compared with hindcast results at 17.5° S latitude and 85° W longitude for the period June - September 1988. Swell heights and mean periods were calculated from the first six frequency bands of both buoy and model data as for buoy 46042 discussed above. No measured directional information is available. It is assumed that the swell energy calculated from the buoy data originates in the Southern Hemisphere. Model results indicate swell is from the Southern Hemisphere along paths not passing islands or shoals. Swell heights and mean periods from the hindcast and measurements for the period June - September 1988 are shown in Figures 12 and 13. Hindcast and measured swell heights are larger at this location than off the California coast. The location is closer to the source region and exposed to a wider window of directions from which swell can approach. Hindcast and measured swell heights agree reasonably. There is a tendency for hindcast swell heights to be higher by about 0.5 to 1.0 m. Hindcast and measured swell periods agree reasonably well.
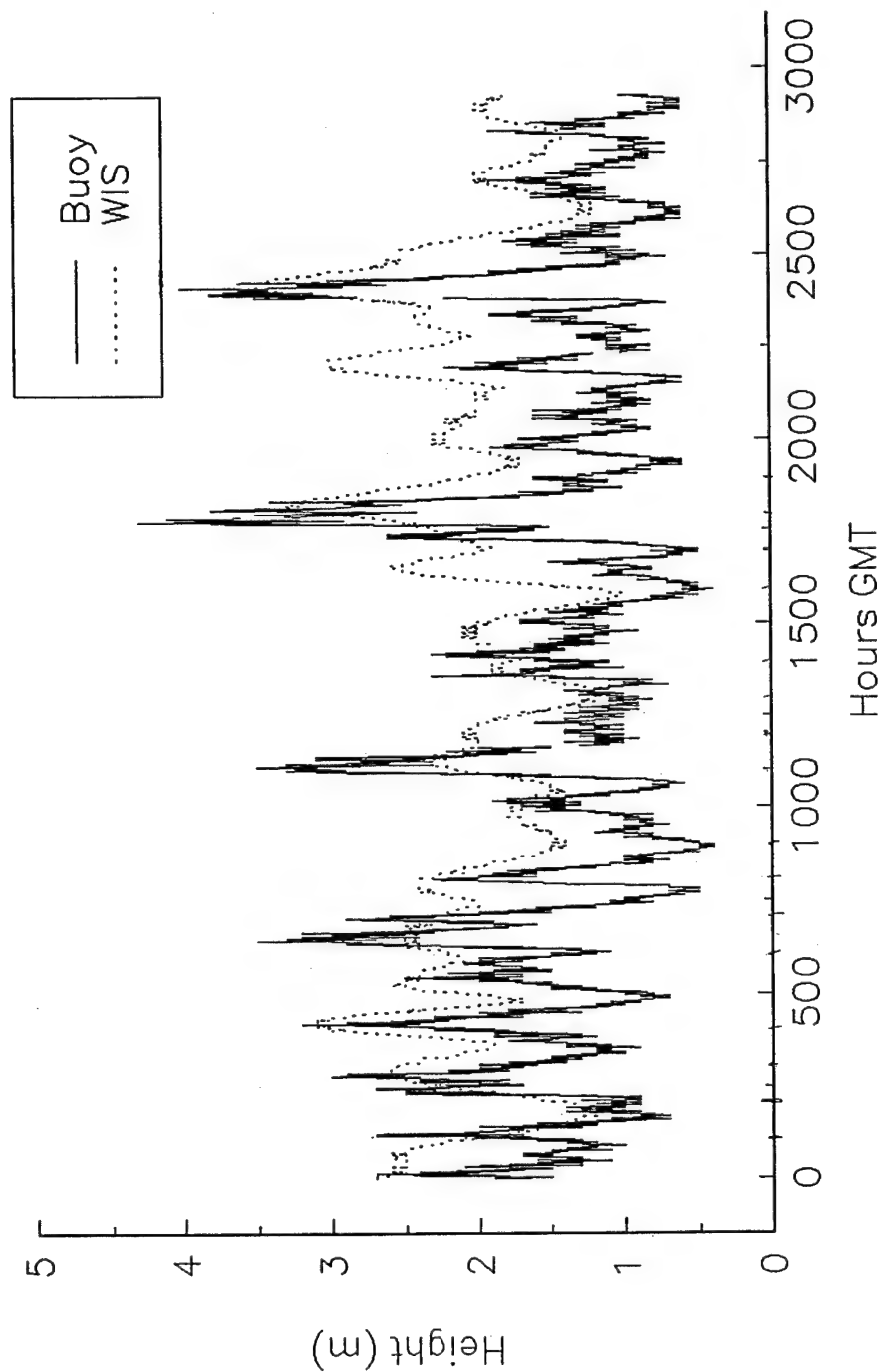
Figure 12. Comparison of measured and hindcast swell height at buoy location 32302 during June - September 1988.
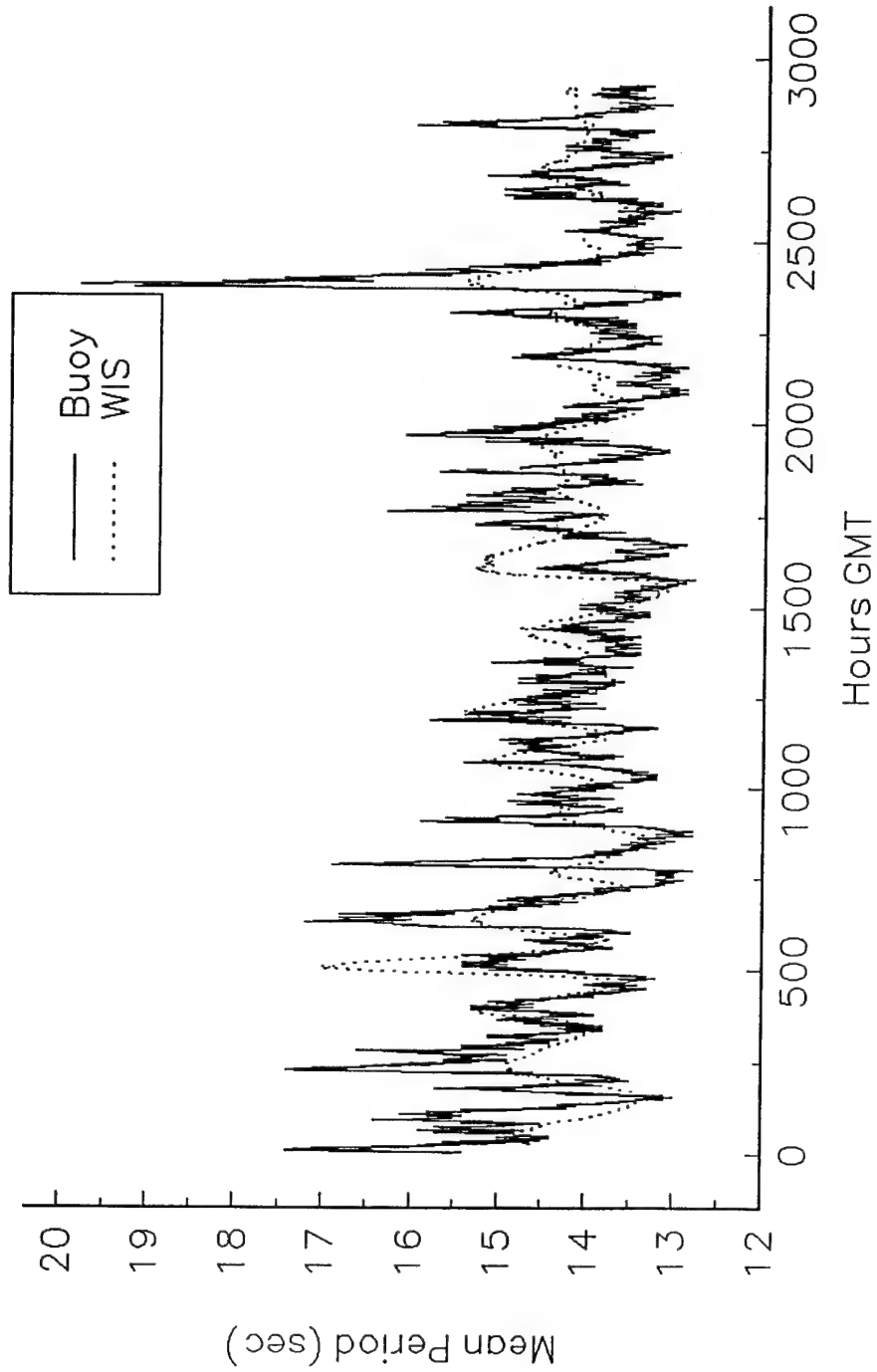
Figure 13. Comparison of measured and hindcast swell mean period at buoy location 32302 during June - September 1988

Events observed at buoy 32302 can be correlated to winds in the Southern Ocean after taking into account the travel time, which is about 6 days based on Equation 2 and a speed of 15.6 m/s. Peaks and troughs in the height and period curves correlate reasonably throughout the 40-month period. For example, the peak in swell heights on 17 July (approximately 1100 hr) is attributed to winds between 145° and 165° W and 30° to 70° S blowing toward the northeast over a 3-day period from 10-12 July. An example of the winds on 11 July is shown in Figure 14. Similar wind patterns cause the peaks in swell on 13 August (1800 hr) and 9 September (2400 hr). The hindcast does reasonably well in matching these events. This implies that, for unobstructed propagation of swell to the South American coast, from wind systems like these the hindcast is accurate to within about 1 m for height and to within 2 s for period. The reason for these errors, especially in height,
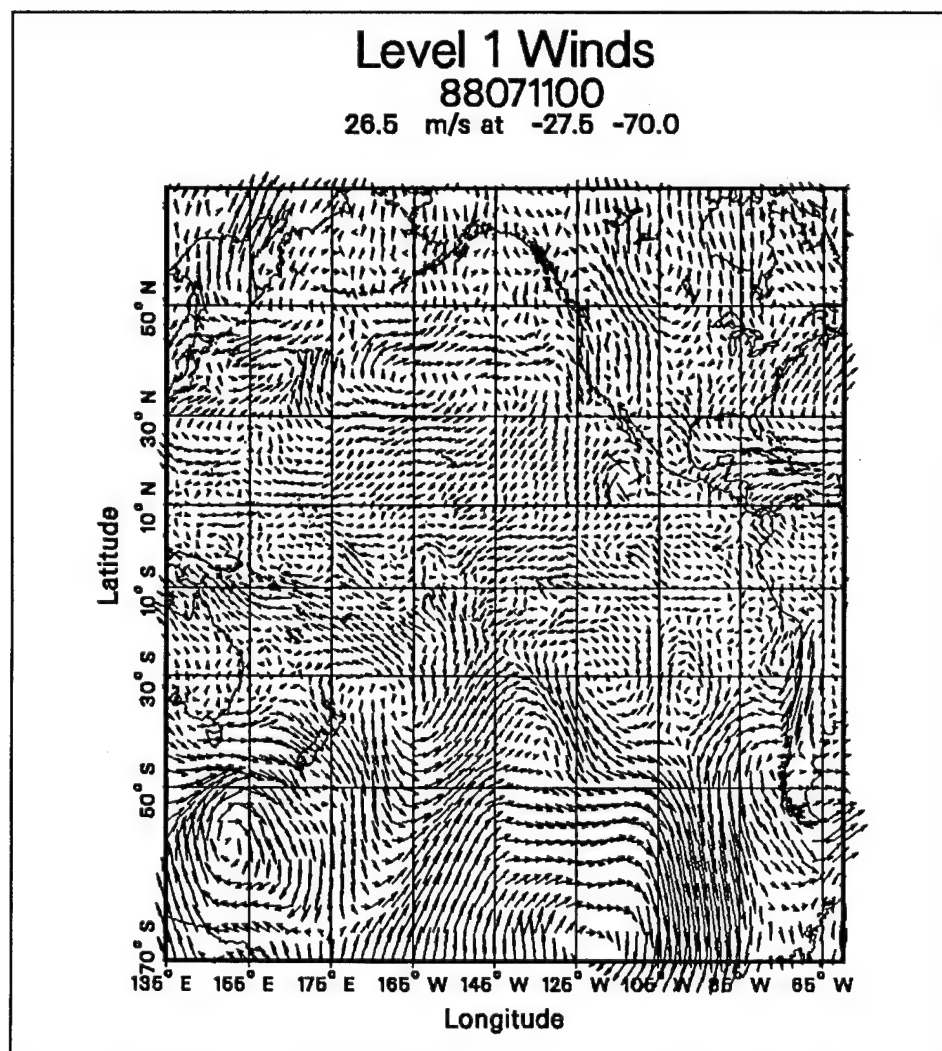
Figure 14. Wind vectors over numerical grid showing storms in Southern Hemisphere on 11 July 1988

could be inaccurate wind speeds and/or directions some of the time. Note that peaks in hindcast and measured swell often agree. Thus, an inappropriate specification of the wind source term in the wave model is probably unlikely. Model results in other applications do not show a tendency for over-prediction of wave heights in strong winds. In fact, for extreme storms, wave heights are probably underpredicted. Inaccurate winds in the source region will also translate into disagreements between measured and hindcast results at buoy 46042. Note that during the first 700 hr in Figures 10 and 12, hindcast heights at both sites agree reasonably well, indicating that winds in the source region were probably fairly accurate.

For those cases in Figures 10 and 11 when hindcast swell heights are larger than measured by a meter or more, it is likely that wind speeds in the source region were over-specified. If sheltering or dissipation were increased to bring these events into agreement with measurements, it is likely that hindcast values would be much too low at times when they would otherwise be in agreement.

If indeed some weather events in the Southern Ocean are not accurately represented in the FNOC winds, it will be difficult to obtain a higher degree of accuracy in hindcasting southern swell. The lack of meteorological information or measured wave data in the region precludes special analysis to identify or improve results for these cases. In practice, the best analysis at this time, using historical data in a hindcast study, would be to identify events which are likely overestimates by testing for some upper limit on hindcast southern swell. This upper limit could be determined by an analysis of measured data. From the analysis done here, the upper limit value would seem to be on the order of 1 m in deep water off the U.S. west coast. This would naturally depend on location. The results from buoy 32302 off the South American coast indicate an upper limit value of about 3 m.

This approach is tested using 1 year of hindcast wave data produced by the U. S. Army Engineer District, San Francisco, for a project at Ocean Beach, California. The directional spectral data from the hindcast were processed as discussed above to obtain southern swell data near the location of buoy 46042. An upper limit on swell height was then imposed to see if the filtered results agree statistically with the values in Table 1.

Hindcast wave results from the San Francisco study are available for 1983 at the same model grid point used previously for comparison to results from buoy 46042. Winds over the entire model grid were used for the entire year and so contain coarse representation of tropical storms causing swell from the south. Swell height, mean period, and mean direction were calculated from model spectra for frequencies less than 0.0833 Hz. The resulting set of values was subsampled to choose only occurrences with angles between 135 and 235 deg. Heights were reduced by 0.5 m to account for the general overestimate in hindcast values by that amount. The resulting values were then limited to heights less than or equal to 1.0 m to exclude large values associated with storms. The resulting data are characterized by the statistics in Table 2.

**Table 2
Summary Statistics for Hindcast Southern Swell
Buoy 46042, 1983**

Statistics	Height, m	Period, s	Direction, deg
Minimum	-0.1*	12.5	160
Maximum	1.1	15.9	235
Mean	0.5	13.7	203
Median	0.5	13.5	201
Std. Deviation	0.3	0.7	18.8
No. of Obs.	1921	1921	1921

* Negative sign due to subtracting 0.5 from all heights.

These statistics are similar to those in Table 1, which implies the presence of at least statistically represented Southern Hemisphere swell after eliminating large wave heights due to tropical storms and adjusting hindcast values to remove a bias of 0.5 m. Without further research and additional information on the winds in the Southern Hemisphere and energy dissipation effects of swell propagation past islands and shoals, this appears to be an acceptable solution to the problem at this time.

One motivation to include Southern Hemisphere swell in the WIS wave climate was to obtain more realistic estimates of longshore sand transport along the southern California coast. If the above approach is applied, and is successful in estimating more accurate sand volume transports, it will verify the approach and be a solution to the problem until more accurate hindcasts are available.

More research could be done on the problem. If pursued, priority should be given to more detailed study of winds in the Southern Ocean area and use of more accurate directional spectral wave data than those being collected presently. The use of wind speed estimates collected from satellites, and alternative wind estimates from other sources, such as the National Meteorological Center and European Centers, should be explored.

6 Summary and Conclusions

The objective of this study was to develop an approach to hindcast swell from the Southern Ocean for use in coastal engineering studies along the U.S. west coast. Swell from the south along the southern California coast is commonly observed, especially in the summer months. Without this component of the wave climate, coastal engineering studies which make use of wave information, such as estimates of longshore sand transport, would not be accurate.

Swell from southerly directions can have a number of sources. This study addressed swell whose source was storms in the Southern Hemisphere. Another source was tropical storms and hurricanes in low latitudes of the Northern Hemisphere. Both of these sources (Southern and Northern Hemisphere) occurred during the same seasons, which made identification of sources from measurements more difficult.

Wave measurements from buoys in the Pacific were examined to characterize the swell component from the Southern Ocean. Since buoys sense waves of all frequencies and directions, it was necessary to select only that energy which was likely to represent swell with a Southern Ocean origin. This was done by considering only energy in certain frequency bands and direction bands when directional information was available. In effect, only a portion of the complete surface of a frequency-direction spectrum was chosen. The limits on frequencies and directions to define the swell portion were subjective. In this study, waves with periods longer than 12.5 s and from directions between 135 and 235 deg were considered the population of swell possible from the Southern Ocean. Measurements at times when tropical storms and hurricanes were present were omitted from the population. The resulting population of measurements from a buoy off the coast of Monterey, California, during 1988 and 1989 indicated a mean height, period, and direction of 0.4 m, 14.5 s, and 184 deg, respectively, for southern swell.

The approach taken to reproduce this population, by hindcasting, was to extend the hindcast grid to the Southern Ocean so that waves would be generated by the storms transiting to the east between New Zealand and the west coast of South America. Winds imposed on the grid to generate the waves were from the Navy's FNOC product, 2.5 deg latitude/longitude, and elevation of 19.5-m wind components. These global winds were produced

from a combination of meteorological measurements and multilevel numerical models of the atmosphere. Naturally, the most accurate representations of actual wind were in areas of dense measurements. Winds in areas where measurements were sparse, such as the Southern Ocean, were representative, but may not have been as accurate.

Swell hindcast near the buoy measurements off Monterey, California, from a hypothetical storm southeast of New Zealand exhibited the mean characteristics of the swell from the buoy measurements. Propagation times and direction to the storm center were consistent with theory.

Results from hindcasts over two summers, omitting times of tropical storms and hurricanes, indicated that model results agreed with measurements only occasionally. Most of the time, hindcast swell heights were within 0.5 m of measurements. Mean periods were generally within 2 s and mean directions within 30 deg. There were times when hindcast swell heights exceeded measured values by a meter. Comparison of hindcast and measured results at other locations of nondirectional buoys indicated similar results for heights and mean periods. Sufficient information was not available to explain the differences when they occurred. It was hypothesized that over-estimation of wind speeds or fetches was the cause of those events when model results exceeded measurements by more than 0.5 m. The general bias of hindcast swell heights of about 0.5 m, with respect to measurements, may have been due to the lack of swell dissipation in the model as swell propagated from the source region to the measurement sites. There was no information, however, to verify this hypothesis.

One year (1983) of hindcast wave information from a typical hindcast study was processed using the criteria of this study to obtain a population of southern swell. Winds from FNOC were imposed over the entire Pacific Ocean for the entire year. No attempt was made to delete periods of tropical storms or hurricanes. Swell heights for all cases were reduced by 0.5 m to account for the apparent bias noted in the 1988-1989 comparisons. All occurrences in the resulting population where swell heights exceeded 1.0 m were then omitted. Omitting these values was based on the assumption that the swell may have been due to tropical storms or hurricanes, or may have been overestimates of swell originating in the Southern Ocean. Tropical storms or hurricanes were not properly represented in the FNOC winds due to a lack of detailed analysis of these storms and the large (2.5-deg) grid spacing of the atmospheric models. The mean, maximum, and number of occurrences of the resulting population agreed with similar statistics obtained from measurements.

These results, although not ideal, are considered satisfactory to represent the mean characteristics of southern swell for coastal engineering purposes. In practice, some method to reduce the bias in swell height should be implemented. Tropical storms and hurricanes should be hindcast separately from the general climate since they require special analysis. Thus, they should be omitted from the winds used on this scale. The remaining events, when

hindcast swell heights exceed measurements, can be adjusted using measurements when available or identified for further analysis using a threshold criteria.

This study addresses the deepwater swell climate originating in the Southern Ocean. In practice, this climate is used at the shore after the swell has refracted and shoaled. Swell conditions at the shore are very sensitive to incident conditions. Differences of 5 deg for incident swell direction can result in large differences of wave conditions at the shore. At present, neither measured nor hindcast wave information is of sufficient accuracy to supply reliable input wave conditions for transformation to shore. Thus, when this hindcast swell climate is transformed to shore, it may not reproduce the measured climate accurately in time. However, over time the mean climate should be representative, and time-integrated products related to wave conditions, such as sand transport, should correctly represent actual conditions.

To improve the present approach, future research in this area should examine the more accurate directional wave spectra now being collected to confirm the statistics of Southern Hemisphere swell. Selected events should be studied in detail to possibly explain the bias in hindcast swell heights and over-prediction during certain events. Satellite data should be examined to verify wind conditions during times when hindcast results agree and disagree with measurements.

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Appendix A
Model Input Options

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 .1900   .2000  .2100  .2200
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13. ABSTRACT *(Maximum 200 words)*

It is well documented that ocean swell arrives at the U.S. Pacific coast, especially southern California, from the Southern Ocean during the Northern Hemisphere summer. This swell can have a major impact on sand transport in the littoral zone as it shoals and breaks on the beach. Hindcast wave information for this region does not contain this component of the wave climate. This report describes a method by which this swell can be included in future wave hindcasts. Buoy wave measurements are analyzed to identify and characterize swell from the Southern Hemisphere. The Wave Information Study wave model WISWAVE 2.0 is used to hindcast swell from a hypothetical storm in the Southern Hemisphere as well as actual storms during the summers of 1988 and 1989. Hindcast results are compared to theory and measurements. Swell heights calculated by the model tend to be higher than those determined from measurements. Differences are attributed to loss of swell energy during propagation through the south Pacific islands not represented in the model and possibly to inaccurate wind speeds and directions over the Southern Ocean. Despite differences, the approach is considered practical if model results are calibrated to measurements.

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